RESPONSE SURFACE METHODOLOGY FOR PREDICTION AND OPTIMISATION OF CONCRETE PROPERTIES CONTAINING COAL BOTTOM ASH

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For my beloved father, mother and family.

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ABSTRACT

The use of Coal Bottom Ash (CBA) as a sand substitute in concrete has become an interesting research topic due to its potential to produce sustainable concrete. Therefore, this study aims to predict and optimise the effect of adding CBA as a sand replacement with different water-cement ratio on the hardened properties of concrete at different curing ages using the Response Surface Method (RSM). Based on Central Composite Design (CCD) of RSM, 18 mixes of various combinations of the independent factors (water-cement ratio: 0.40─0.50, percentage of CBA replacement: 5─20%, and curing age: 28─56 days) were generated, and two responses (compressive strength and water absorption) were investigated. The results show that the 5% CBA replacement at a water-cement ratio of 0.40 produced the highest compressive strength. Nonetheless, it is weaker than control concrete. When the concrete mix has a water-cement ratio of 0.45 with lowest CBA replacement of 5%, the CBA concrete has a significant effect, which surpassed the control concrete. It has been observed that concrete with up to 20% CBA absorbs less water at all ages. The results of Analysis of Variance (ANOVA) and statistical validation methods showed that all models were robust, reliable, and significant. The coefficient of determination (R^2) for both models is near to 1 ($R^2 > 0.94$) and variation data less than 5%, demonstrating that the suggested model equations can predict future observations. In a nutshell, the use of CBA as concrete materials could minimise the consumption of natural resources while preserving the environment. The implementation of RSM in the concrete industrial sector helps to save costs, save time, and make more efficient use of main power.

ABSTRAK

Penggunaan abu dasar arang batu (CBA) sebagai pengganti pasir dalam konkrit telah menjadi topik kajian yang menarik kerana ianya berpotensi untuk menghasilkan konkrit yang mampan. Oleh itu, kajian ini bertujuan untuk meramal dan mengoptimumkan kesan penambahan CBA sebagai pengganti pasir dengan nisbah air-simen yang berbeza keatas sifat keras konkrit pada umur pengawetan yang berbeza dengan menggunakan kaedah gerak balas permukaan (RSM). Berdasarkan rekabentuk komposit berpusat (CCD) dalam RSM, 18 campuran pelbagai kombinasi faktor input (nisbah air-simen: 0.40─0.50, peratusan penggantian CBA: 5─20%, dan umur pengawetan: 28─56 hari) adalah dihasilkan, dan dua tindakbalas (kekuatan mampatan dan penyerapan air) telah disiasat. Keputusan menunjukkan penggantian CBA pada 5% dengan nisbah air-simen 0.40 menghasilkan kekuatan mampatan tertinggi. Walau bagaimanapun, ia lebih rendah daripada konkrit kawalan. Apabila campuran konkrit berubah ke nisbah air-simen 0.45 dengan penggantian CBA serendah 5%, konkrit CBA menunjukkan kesan yang ketara, iaitu mengatasi konkrit kawalan. Selain itu, juga telah diperhatikan bahawa konkrit dengan penambahan CBA sehingga 20% menyerap sedikit air pada semua peringkat umur. Keputusan analisis varians (ANOVA) dan kaedah pengesahan statistik menunjukkan bahawa semua model adalah teguh, boleh dipercayai, dan signifikan. Nilai pekali penentuan (R^2) untuk kedua-dua model adalah menghampiri nilai 1 (R^2 >0.94) dan data variasi didapati kurang daripada 5%, menunjukkan bahawa persamaan model yang dicadangkan boleh meramalkan sifat konkrit CBA pada masa hadapan. Secara ringkasnya, penggunaan CBA sebagai bahan konkrit boleh meminimumkan penggunaan sumber asli di samping memelihara alam sekitar. Penggunaan RSM dalam sektor industri konkrit membantu menjimatkan kos, menjimatkan masa, dan membantu menggunakan kuasa utama dengan lebih cekap.

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LIST OF SYMBOLS AND ABBREVIATIONS

BS	-	British Standard
ASTM	-	American Society for Testing and Materials
CBA	-	Coal Bottom Ash
RSM	-	Response Surface Method
CCD	-	Central Composite Design
FC-CCD	-	Face-Centred Central Composite Design
SDG	-	Sustainable Development Goal
SEM	-	Scanning Electron Microscope
XRF	-	X-Ray Fluorescence
OPC	-	Ordinary Portland cement
LOI	-	loss of Ignition
MPa	-	Mega-Pascal
N/mm^2	-	Newton per meter square
Kg/m^2	-	Kilogram per meter cube
Cm	-	Centimetre
Mm	-	Millimetre
◦C	-	Degree Celsius
%	-	Percentage
µ	-	Micron

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Environmental issues are a worldwide concern, and the overabundance of waste resources significantly contributes to these concerns. Population growth, rapid industrial and economic growth have resulted in increased waste resources. In particular, coal ash waste has been identified as one of the waste resources. It is produced in response to the coal combustion process in electrical power plants. In fact, the rising demand for the use of electrical power can increase the use of coal. Most power plants around the world utilise coal as their main substance in order to produce electrical power. According to Abdullah et al. (2018), coal is the most cost-effective and abundant resource compared to oil and natural gas. Hence, it has gained recognition around the world. Apart from that, Khongpermgoson et al. (2020) stated that the statistics of overall power consumption for Thailand and Southeast Asia will push up the power requirement to almost 80% due to 2036. The electrical consumption in Peninsular Malaysia will be produced from coal and gas (58% and 25%) in coming 2024 (Rafieizonooz et al., 2016). Despite this, numerous power plants in Malaysia exercised coal as their main source, including the Kapar, Manjung, Sejingkat, Jimah, and Tanjung Bin Power Plants (Ibrahim et al., 2019). In general, the coal ash waste was made up of non-combustible components present in coal. Several coal ash wastes, including Coal Bottom Ash (CBA), were produced during the combustion process. It is called CBA since it is collected at the bottom of the furnace in a coal-fired power plant. Nonetheless, it has been reported that the annual production of CBA in India is about 25 million tones, 14 million tones in the United States, 4 million tones in Europe, and 1.6 million tones in Malaysia (Mangi et al., 2019). These wastes are expected to be produced in large amounts in the future due to the demand for power consumption.

Besides that, in the effort to maintain a cleaner and greener environment, developing sustainable solutions for the safe disposal of industrial waste has become a global concern. In the industries and research fields, the reuse of waste materials has earned great interest (Salleh et al., 2021). The construction materials such as natural sand are highlighted in this research since these resources are depleted due to rising demand for concrete production. Considering the sustainable development of construction materials, exercising CBA as a partial replacement for fine aggregate has emerged as an innovative approach to conserve the resources of natural sand. Moreover, this approach will reduce the environmental issues related to industrial waste disposal. Numerous researchers have discovered that using CBA as a partial replacement for sand aggregate in concrete is acceptable (Al-fasih et al., 2019; Ghadzali et al., 2020; Jawahar et al., 2019; Hannan et al., 2020; Singh & Siddique, 2014, 2015). The strength properties of concrete utilising CBA as fine aggregate has been reported to have indicated encouraging results. However, there were certain limits, such as a lower level of strength and concerns regarding differing data gathered from previous studies. In addition, most studies have discovered that 10-20% CBA replacement to sand satisfied strength development (Al-fasih et al., 2019; Ghadzali et al., 2020; Jawahar et al., 2019; Muthusamy et al., 2021). Despite the fact that numerous researchers have studied these works to determine the optimal percentage replacement of CBA, there is a lack of literature on the use of various water-cement ratios in CBA concrete. It is crucial to determine the proper water-cement ratio since CBA is known to absorb a lot of water and also its chemical properties influence its strength. Due to this, further investigation of CBA as sand replacement with different water-cement ratios is needed to find the optimal amount of CBA concrete as well as its influence on concrete properties.

In a few decades, most researchers have focused on predicting and optimising the properties of different composites through modelling tools rather than the conventional method (Algaifi et al., 2021; Awolusi et al., 2019; Mhaya et al., 2022; Nazerian et al., 2018). The conventional method is often expensive and time-consuming. However, the Response Surface Method (RSM) modelling tools have been brought into engineering fields. For instance, RSM is one of the most well-known statistical and mathematical approaches for making predictions (Haque et al., 2021). This approach employs an input parameter function to set up the output parameters or responses (Poorarbabi, Ghasemi & Moghaddam, 2020). In addition, RSM is often utilised to find the optimal set of inputs to optimise the output response (Sultana et al., 2020). It is advantageous for RSM, which provides a mathematical solution to a problem, reduces the number of experimental trials, and saves time as well as costs (Chong et al., 2021). According to Hammoudi et al. (2019), RSM has been utilised most often in the field of concrete materials to make predictions regarding the characteristics of concrete. In past studies, Sourav et al. (2021) utilised RSM to predict concrete's compressive strength and splitting tensile strength using Fine Glass Aggregate (GFA) waste and Condensed Milk Can (tin) Fibres (CMCF). Besides, Algaifi et al. (2022) also exploited RSM to optimise and predict the mechanical characteristics of Coconut Shell (CS) concrete. Other studies by Khataei & Nasrollahi (2020) employed RSM to optimise the tensile strength of concrete incorporating coal waste, considering the cost. There have been numerous studies on the application of RSM in the concrete fields (Algaifi et al., 2022; Elevado, Galupino & Gallardo, 2019; Haque et al., 2021; Sinkhonde et al., 2021). However, research on using RSM to predict and optimise the harden properties of CBA concrete was limited. In addition, since water affects the strength of concrete, it is essential to investigate water absorption. Prior to that, the independent and dependent parameters must be determined in order to execute the RSM experimental design.

This research work is to study the potential application of CBA as a partial replacement of fine aggregate in concrete through compressive strength and water absorption. In addition, the effects of the water-cement ratios on the compressive strength and water absorption of CBA concrete are also looked into since CBA materials absorb a substantial amount of water. Despite this, the RSM models are developed to obtain the optimisation of design mix. The primary objective of this study is to assess how the compressive strength and water absorption properties of CBA concrete are impacted by varying water-cement ratios and levels of CBA replacement during different stages of curing, applying the RSM method. Ultimately, the effectiveness of the RSM model in predicting and optimising the properties of CBA concrete will be analysed and discussed in the final research report.

1.2 Problem Statement

The environmental issue related to the disposal problem is considered the main factor of this research to examine the potential use of CBA. In general, CBA is well known as a non-combustible material produced from the furnace's combustion in thermal power plants. Indeed, as it is the cheapest and most abundant of material resources, coal is the most desired compared to oil and gas. The rising usage of coal presents new challenges, particularly environmental issues. Other than that, the annual production of CBA was substantial. It makes up around 20% of the total amount of coal ash. However, CBA does not see a specific application for it. In particular, the CBA was disposed of in open land, landfills, or ash ponds in thermal power plants. As a result, an excessive amount of CBA was stored, resulting in decades of environmental pollution issues. In the current scenario, it is becoming a serious concern due to the limitation of dumping sites and the continued production rate. Note that the high amount of CBA at dumping sites might cause a risk to human health and the environment due to harmful chemicals. According to Hasim et al. (2022), high concentrations of toxic metals in CBA can pollute soil and groundwater, contributing to environmental issues. Besides, Hannan et al. (2020) stated that CBA has been classified as toxic because it contains chemical compounds that can cause cancer, reproductive problems, and developmental disorders.

The construction materials, such as natural sand, become a concern in this research. In global, the natural resources of river sand were depleted due to increased demand for concrete manufacturing. Due to this, the research of innovative approaches to sustainable development has captured interest worldwide. Conversely, using CBA as a partial replacement for fine aggregate has become an interesting solution to disposal issues. In addition, it decreases environmental issues and safeguards natural resources. In the past, numerous researchers have studied the use of CBA as a fine aggregate in concrete (Al-fasih et al., 2019; Ghadzali et al., 2020; Jawahar et al., 2019; Hannan et al., 2020; Singh & Siddique, 2014, 2015). It was observed that CBA particles resembled sand particles. Therefore, the studies suggested a significant correlation with respect to their strength. However, there were still results in a change in the data gathered. Rodriguez-Alvaro et al. (2021) claimed that it is difficult to determine the appropriate design mix as the properties of CBA from various sources have changed. Due to this, it becomes a main problem that needs to be tackled before getting official approval for use.

Besides, researchers often applied the conventional method to determine the characteristics of concrete. The conventional method required many experiments to achieve the desired output. Despite this, it required a considerable time and had a high cost of manufacture. In addition, the alternative method known as the RSM will be utilised to solve this issue. In particular, RSM is a powerful statistical parameter tool for designing experiments that can explore the mathematical relationship between input and output factors with a small number of experiments (Haque et al., 2021). It is a method for determining the optimal value of numerous independent variables to obtain desirable products (Breig & Luti, 2021). Moreover, RSM has the potential to predict or model the responses (Hammoudi et al., 2019). Nevertheless, there have been several studies on the use of RSM to cement and concrete (Habibi, Ramezanianpour & Mahdikhani, 2021; Haque et al., 2021; Hassan et al., 2020), but there has been limited research on the application of RSM in concrete modified with CBA as sand replacement. Therefore, this research explored the potential effects of CBA as a substitute for sand in concrete. Meanwhile, this research applied the RSM approach to predict and optimise the hardened properties of this CBA concrete.

1.3 Research Objective

This research investigates the potential application of CBA as a partial replacement for fine aggregate in concrete. In particular, RSM's optimisation and prediction tools have been implemented in this research. Thus, the number of objectives for this research has been established as follows:

1. To characterise the properties of Coal Bottom Ash (CBA) as a sand replacement.
2. To predict the compressive strength and water absorption of Coal Bottom Ash (CBA) concrete using Response Surface Method (RSM).
3. To optimise the effects of water-cement ratio and percentage of Coal Bottom Ash (CBA) replacement on compressive strength and water absorption at different curing ages using Response Surface Method (RSM).

1.4 Research Scope

This research focuses on the role of CBA in concrete as a sand substitute. This main material was sourced from the Manjung Power Plant in Perak. The materials investigation was conducted to determine the properties of fine aggregate (sand) and CBA. The particle size distribution, fineness modulus, specific gravity, water absorption, microstructure, and chemical tests have all been examined. The slump tests were conducted to evaluate the fresh properties of CBA concrete. The compressive strength and water absorption tests were performed to achieve the desired goal in this research. All methods and testing were performed in accordance with the British Standard (BS) and the American Society for Testing and Materials (ASTM), as described in Chapter 3.

The mixed concrete design ratio was calculated using the Design of Normal Concrete, and the concrete with grade 30 MPa represents the target's strength. In order to predict and optimise the desired responses by the experimental approach of RSM, the independent and dependent parameters have been identified. In addition, Design-Expert v13 (Stat-Ease, Inc.) software was applied to perform the experiments. In this research, the water-cement ratio, percentage of CBA replacement, and curing time were independent factors, whereas compressive strength and water absorption were considered dependent. In particular, the independent factors for the water-cement ratio measured between 0.40–0.50, while the percentage CBA replacement was between 5%–20% (in weight), and the curing ages measured at 28–56 days.

In RSM, it generates the experimental design. The amount of CBA, fine aggregate, coarse aggregate, and water-cement ratio varied based on the generated variables proportioning. However, the water contents were fixed for all the generated mixes, which is 190 kg/m^3, as discussed in Chapter 3. In this research, RSM creates 18 experimental designs to evaluate the combined effects of water-cement ratio, percentage of CBA replacement, and curing ages on CBA concrete's compressive strength and water absorption. Three normal concrete designs for 0.40, 0.45, and 0.50 were considered control concrete. In all, 21 mixed designs were examined in this research. However, considering three specimens for each sample, 100 mm cubes were used to cast 144 specimens according to the RSM design and control design. In the end, the comparisons between RSM and the actual experimental testing have been made in conclusion, and RSM models' effectiveness, robustness, and trustworthiness have been proven.

1.5 Research Significant

Utilising industrial wastes, such as CBA, as a sand replacement in concrete manufacturing can help create a sustainable future. It has been expected that the significant and productive use of CBA can potentially ease the burden on the natural resources of sand and preserve the environment. Evidence in the literature suggests that replacing sand aggregate in concrete with CBA at a certain percentage improves mechanical properties. Until now, finding the appropriate design mix has been difficult since the material characteristics and just a few published results were often inconsistent. In particular, as CBA particles have a porous structure as well as absorbed materials, it has a major influence on the properties of concrete. The finding of the exact water-cement ratio becomes complicated due to the highly porous structure of CBA. Therefore, this research examines the hardened properties of concrete containing CBA as a partial substitute for fine aggregate, considering the different water-cement ratios.

Besides, modelling tools such as the RSM also attract attention in this research. This method helps the researchers predict and optimise CBA concrete's hardened properties. In addition, it offers a comprehensive data presentation with minimal experimental design compared to the conventional method. On the other hand, if the disposal problems and environmental impacts can be resolved. Subsequently, using the RSM approach in concrete fields has assured effective material usage, reducing production costs and time-consuming. This research also meets the Sustainable Development Goal (SDG) requirement in the nine-goal: industrial, innovative, and infrastructure. Furthermore, this approach could play the main role in encouraging innovation and promoting technological progress. As a result, this approach is important in finding long-term solutions to economic and environmental challenges.

REFERENCES

Abdulkadir, I., Mohammed, B. S., Liew, M. S., & Wahab, M. M. A. (2021). Modelling and multi-objective optimization of the fresh and mechanical properties of self-compacting high volume fly ash ECC (HVFA-ECC) using response surface methodology (RSM). *Case Studies in Construction Materials*, *14*(3), 525–536.

Abdullah, M. H., Rashid, A. S. A., Anuar, U. H. M., Marto, A., & Abuelgasim, R. (2019). Bottom ash utilization: A review on engineering applications and environmental aspects. *IOP Conference Series: Materials Science and Engineering, 527*(1), 1206–1213.

Abdullah, M. H., Abuelgasim, R., Rashid, A. S. A., & Mohdyunus, N. Z. (2018). Engineering properties of Tanjung Bin bottom ash. *MATEC Web of Conferences*, *250*(12), 1006–1014.

Abdulmatin, A., Tangchirapat, W., & Jaturapitakkul, C. (2018). An investigation of bottom ash as a pozzolanic material. *Construction and Building Materials, 186*(8), 155–162.

Amr, S. S. A., Aziz, H. A., & Bashir, M. J. K. (2014). Application of Response Surface Methodology (RSM) for Optimization of Semi-Aerobic Landfill Leachate Treatment Using Ozone. *Sewage and Landfill Leachate: Assessment and Remediation of Environmental Hazards, 4*(3), 231–239.

Adamu, M., Ayeni, K. O., Haruna, S. I., Mansour, Y. E. -H. I, & Haruna, S. (2021). Durability performance of pervious concrete containing rice husk ash and calcium carbide: A response surface methodology approach. *Case Studies in Construction Materials*, *14*(5), 547–552.

Al-fasih, M. Y. M., Haziman, M., Ibrahim, W., & Basirun, N. F. (2019). Influence of partial replacement of cement and sand with coal bottom ash on concrete properties. *International Journal of Recent Technology and Engineering, 8*(3), 356–362.

Algaifi, H. A., Mohamed, A. M, Alsuhaibani, E., Shahidan, S., Alrshoudi, F., Huseien, G. F., & Bakar, S. A. (2021). Optimisation of GBFS, fly ash, and nano-silica contents in alkali-activated mortars. *Polymers, 13*(16), 2750–2762.

Algaifi, H. A., Shahidan, S., Zuki, S. S. M., Ibrahim, M. H. W., Huseien, G. F., & Rahim, M. A. (2022). Mechanical properties of coconut shell-based concrete: experimental and optimisation modelling. *Environmental Science and Pollution Research, 29*(14), 21140–21155.

Almajed, A., Srirama, D., & Moghal, A. A. B. (2021). Response surface method analysis of chemically stabilized fiber-reinforced soil. *Materials, 14*(6), 1535–1541.

Andrade, L. B., Rocha, J. C., & Cheriaf, M. (2009). Influence of coal bottom ash as fine aggregate on fresh properties of concrete. *Construction and Building Materials, 23*(2), 609–614.

Abidin, N. E. Z., Ibrahim, M. H. W., Jamaluddin, N., Kamaruddin, K., & Hamzah, A. F. (2014). The effect of bottom ash on fresh characteristic, compressive strength and water absorption of self-compacting concrete. *Applied Mechanics and Materials, 660*(3), 145–151.

Ankur, N., & Singh, N. (2021). Performance of cement mortars and concretes containing coal bottom ash: A comprehensive review. *Renewable and Sustainable Energy Reviews, 149*(1), 1113–1126.

Aouan, B., Alehyen, S., Fadil, M., El, M., Khabbazi, A., Atbir, A., & Taibi, M. (2021). Compressive strength optimization of metakaolin-based geopolymer by central composite design. *Chemical Data Collections, 31*(2), 636–641.

Awolusi, T.F., Oke, O. L., Akinkurolere, O. O., & Sojobi, A. O. (2019). Application of response surface methodology: Predicting and optimizing the properties of concrete containing steel fibre extracted from waste tires with limestone powder as filler. *Case Studies in Construction Materials, 10*(9), 212–225.

Awolusi, T. F., Oke, L. O., Akinkurolere, O. O., Ubani, D. P., Bamisaye, R. T., & Aluko, O. G. (2021). The application of response surface methodology in understanding the compressive strength and water absorption capacity of sandcrete blocks. *Silicon, 13*(11), 4123–4132.

Ayob, A., Zahid, M. Z. A. M., Zaki, M. F. M., Hamid, S. H. A., Yussuf, M. A. H. M., & Yunus, A. N. M. (2014). Physical, morphological and strength properties of Jana Manjung coal ash mixture for geotechnical applications. *Advances in Environmental Biology, 8*(22), 25–29.

Azhar, F. N. A., Taha, M. F., Ghani, S. M. M., Ruslan, M. S. H., & Yunus, N. M. M. (2022). Experimental and mathematical modelling of factors influencing carbon dioxide absorption into the aqueous solution of monoethanolamine and 1-butyl-3-methylimidazolium dibutylphosphate using response surface methodology (RSM). *Molecules, 27*(6), 1779–1792.

ASTM International. *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*. United States, ASTM C618. 2022.

Baite, E., Messan, A., Hannawi, K., Tsobnang, F., & Prince, W. (2016). Physical and transfer properties of mortar containing coal bottom ash aggregates from Tefereyre (Niger). *Construction and Building Materials, 125*(10), 919–926.

Bashir, M. J. K., Amr, S. S. A., Aziz, S. Q., Aun, N. C., Sethupathi, S., Technology, G., Tunku, U., & Rahman, A. (2015). Wastewater treatment processes optimization using response surface methodology (RSM) compared with conventional methods: Review and comparative study. *Middle-East Journal of Scientific Research, 23*(2), 244–252.

Behera, S. K., Meena, H., Chakraborty, S., & Meikap, B. C. (2018). Application of response surface methodology (RSM) for optimization of leaching parameters for ash reduction from low-grade coal. *International Journal of Mining Science and Technology, 28*(4), 621–629.

Breig, S. J. M., & Luti, K. J. K. (2021). Response surface methodology: A review on its applications and challenges in microbial cultures. *Materials Today: Proceedings, 42*(7), 2277–2284.

British Standards Institution. *Test Sieves (Technical Requirements and Testing) – Part 1: Test Sieves of Metal Wire Cloth*. London, BS 410. 2000.

British Standards Institution. *Specification for Aggregates from Natural Sources for Concrete*. London, BS 882. 1992.

British Standards Institution. *Aggregate for Concrete*. London, BS EN 12620: 2002 +A1. 2008.

British Standards Institution. *Cement – Part 1: Composition, Specifications and Conformity Criteria for Common Cements*. London, BS EN 197. 2011.

British Standards Institution. *Mixing Water for Concrete. Specification for Sampling, Testing and Assessing the Suitability of Water, Including Water Recovered from Processes in the Concrete Industry, as Mixing Water for Concrete*. London, BS EN 1008. 2002.

British Standards Institution. *Testing Aggregates – Part 2: Methods of Determination of Density*. London, BS 812. 1995.

British Standards Institution. *Tests for Mechanical and Physical Properties of Aggregates – Part 6: Determination of Particle Density and Water Absorption*. London, BS EN 1097. 2022.

British Standards Institution. *Microbeam Analysis. Scanning Electron Microscopy. Guidelines for Calibrating Image Magnification.* Switzerland, BS ISO 16700. 2016.

British Standards Institution. *Testing Fresh Concrete – Part 2: Slump Test.* London, BS EN 12350. 2019.

British Standards Institution. *Testing hardened concrete – Part 3: Compressive Strength of Test Specimens*. London, BS EN 12390. 2009.

British Standards Institution (2011). *Testing concrete – Part 122: Method for determination of Water Absorption*. London, BS EN 1881. 2011.

Cira, S. C., Dag, A., & Karakus, A. (2016). Application of response surface methodology and central composite inscribed design for modeling and optimization of marble surface quality. *Advances in materials science and engineering, 20*(6), 1–13.

Chand, G., Ram, S., Kumar, S., & Gupta, U. (2021). Microstructural and engineering properties investigation of sustainable hybrid concrete produced from industrial wastes. *Cleaner Engineering and Technology, 2*(9), 52–63.

Chong, W., Othman, R., Putra, R., Li, X., Rosli, M., Hasan, M., Mustafa, M., & Bakri, A. (2021). Meta-analysis of studies on eggshell concrete using mixed regression and response surface methodology. *Journal of King Saud University – Engineering Sciences, 35*(4), 279–287.

Despotovic, M., Nedic, V., Despotovic, D., & Cvetanovic, S. (2016). Evaluation of empirical models for predicting monthly mean horizontal diffuse solar radiation. *Renewable and Sustainable Energy Reviews*, *56*(4), 246–260.

Dacuba, J., Cifrian, E., Romero, M., Liono, T., & Andres, A. (2022). Influence of unburned carbon on environmental-technical behaviour of coal fly ash fired clay bricks. *Applied Sciences*, *12*(8), 3765–3772.

Elevado, K. J. T., Galupino, J. G., & Gallardo, R. S. (2019). Compressive strength optimization of concrete mixed with waste ceramics and fly ash. *International Journal of GEOMATE, 16*(53), 135–140.

Faisal, S. K., Mazenan, P. N., Shahidan, S., & Irwan, J. M. (2018). Review of coal bottom ash and coconut shell in the production of concrete. *IOP Conference Series: Materials Science and Engineering*, *342*(1), 32–41.

Ghadzali, N. S., Ibrahim, M. H. W., Sani, M. S. H. M., Jamaludin, N., Desa, M. S. M., & Misri, Z. (2018). Properties of concrete containing different type of waste materials as aggregate replacement exposed to elevated temperature – A review. *IOP Conference Series: Earth and Environmental Science*, *140*(1), 39–48.

Ghadzali, N. S., Ibrahim, M. H. W., Zuki, S. S. M., Sani, M. S. H., & Al-Fasih, M. Y. M. (2020). Material Characterization and Optimum Usage of Coal Bottom Ash (CBA) as Sand Replacement in Concrete. *International Journal of Integrated Engineering*, *12*(9), 9–17.

Ghafari, S., Aziz, H. A., Isa, M. H., & Zinatizadeh, A. A. (2009). Application of response surface methodology (RSM) to optimize coagulation-flocculation treatment of leachate using poly-aluminum chloride (PAC) and alum. *Journal of Hazardous Materials, 163*(3), 650–656.

Ghosh, A., Ghosh, A., & Neogi, S. (2021). Evaluation of physical and thermal properties of coal combustion residue blended concrete for energy efficient building application in India. *Advances in Building Energy Research, 15*(3), 315–336.

Gooi, S., Mousa, A. A., & Kong, D. (2020). A critical review and gap analysis on the use of coal bottom ash as a substitute constituent in concrete. *Journal of Cleaner Production*, *268(9)*, 52–68.

Govindarajan, D., Keerthana, M., Raja, G. K., & Kumar, R. P. (2018). Replacement of Fine Aggregate with Bottom Ash in Concrete and Investigation on Compressive Strength. *International Journal of ChemTech Research*, *6*(8), 189–196.

Habibi, A., Ramezanianpour, A. M., & Mahdikhani, M. (2021). RSM-based optimized mix design of recycled aggregate concrete containing supplementary cementitious materials based on waste generation and global warming potential. *Resources, Conservation and Recycling*, *167*(10), 220–231.

Hammoudi, A., Moussaceb, K., Belebchouche, C., & Dahmoune, F. (2019). Comparison of artificial neural network (ANN) and response surface methodology (RSM) prediction in compressive strength of recycled concrete aggregates. *Construction and Building Materials, 209*(4), 425–436.

Hamada, H., Alattar, A., Tayeh, B., & Yahaya, F. (2022). Sustainable application of coal bottom ash as fine aggregates in concrete: A comprehensive review. *Case Studies in Construction Materials, 16*(5), 1109–1118.

Haque, M., Ray, S., Mita, A. F., Bhattacharjee, S., & Shams, J. B. (2021). Prediction and optimization of the fresh and hardened properties of concrete containing rice husk ash and glass fiber using response surface methodology. *Case Studies in Construction Materials, 14*(7), 1–14.

Hasim, A. M., Shahid, K. A., Ariffin, N. F., Nasrudin, N. N., & Zaimi, M. N. S. (2022). Properties of high volume coal bottom ash in concrete production. *Materials Today: Proceedings, 48*(2), 1861–1867.

Hassan, M. Z., Roslan, S. A., Sapuan, S. M., Rasid, Z. A., Nor, A. F. M., Daud, M. Y. M., Dolah, R., & Yusoff, M. Z. M. (2020). Mercerization optimization of bamboo (Bambusa vulgaris) fiber-reinforced epoxy composite structures using a Box–Behnken design. *Polymers, 12*(6), 1367–1372.

Hannan, N. I. R. R., Shahidan, S., Ali, N., Bunnori, N. M., Zuki, S. S. Z., & Ibrahim, M. H. W. (2020). Acoustic and non-acoustic performance of coal bottom ash concrete as sound absorber for wall concrete. *Case Studies in Construction Materials, 13*(1), 399–409.

Hannan, N. I. R. R., Shahidan, S., Ali, N., & Maarof, M. Z. (2017). A comprehensive review on the properties of coal bottom ash in concrete as sound absorption material. *MATEC Web of Conferences, 103*(8), 1–10.

Ibrahim, A. H., Keong, C. K., Johari, M. A. M., Rashid, M. R. M., & Ariffin, K. S. (2019). Influence of coal bottom ash on properties of Portland cement mortar. *International Journal of Integrated Engineering, 11*(2), 69–77.

Ibrahim, M. H. W., Hamzah, A. F., Jamaluddin, N., Ramadhansyah, P. J., & Fadzil, A. M. (2015). Split tensile strength on self-compacting concrete containing coal bottom ash. *Procedia - Social and Behavioral Sciences, 195*(8), 2280–2289.

Isam, M., Baloo, L., Kutty, S. R. M., & Yavari, S. (2019). Optimisation and modelling of Pb(II) and Cu(II) biosorption onto red algae (Gracilaria changii) by using response surface methodology. *Water (Switzerland), 11*(11), 1–12.

International Standard. *Iron Ores — Determination of Various Elements by X-Ray Fluorescence Spectrometry — Part 1: Comprehensive Procedure*. Switzerland, ISO 9516. 2003.

Jaber, H. A., Mahdi, R. S., & Hassan, A. K. (2020). Influence of eggshell powder on the Portland cement mortar properties. *Materials Today: Proceedings, 20*(3), 391–396.

Jawahar, S., Magesh, M., Jagen, V., & Vasugi. (2019). Performance evaluation of concrete using bottom ash as fine aggregate. *International Journal of Innovative Technology and Exploring Engineering, 8*(7), 95–100.

Jorat, M. E., Marto, A., Namazi, E., & Amin, M. F. M. (2011). Engineering characteristics of kaolin mixed with various percentages of bottom ash. *Electronic Journal of Geotechnical Engineering*, *16*(5), 841–850.

Karimifard, S., & Moghaddam, M. R. A. (2018). Application of response surface methodology in physicochemical removal of dyes from wastewater: A critical review. *Science of the Total Environment*, *641*(11), 772–797.

Khaleel, O. J., Ibrahim, T. K., Ismail, F. B., & Al-Sammarraie, A. T. (2021). Developing an analytical model to predict the energy and exergy based performances of a coal-fired thermal power plant. *Case Studies in Thermal Engineering, 28*(8), 519–525.

Khan, M. I., Sutanto, M. H., Napiah, M. B., Zahid, M., & Usman, A. (2020). Optimization of Cementitious Grouts for Semi-Flexible Pavement Surfaces Using Response Surface Methodology. *IOP Conference Series: Earth and Environmental Science, 498*(1), 2004–2012.

Kadam, M. P., & Patil, Y. D. (2014). The effect of sieved coal bottom ash as a sand substitute on the properties of concrete with percentage variation in cement. *American Journal of Civil Engineering and Architecture, 2*(5), 160–166.

Khataei, B., & Nasrollahi, M. (2020). Optimizing the tensile strength of concrete containing coal waste considering the cost. *SN Applied Sciences, 2*(1), 1–13.

Khongpermgoson, P., Boonlao, K., Ananthanet, N., Thitithananon, T., Jaturapitakkul, C., Tangchirapat, W., & Ban, C. C. (2020). The mechanical properties and heat development behaviour of high strength concrete containing high fineness coal bottom ash as a pozzolanic binder. *Construction and Building Materials, 253*(3), 9239–9244.

Lo, F., Lee, M., & Lo, S. (2021). Effect of coal ash and rice husk ash partial replacement in ordinary Portland cement on pervious concrete. *Construction and Building Materials, 286*(1), 2947–2953.

Manan, T. S. B. A., Beddu, S., Mohamad, D., Kamal, N. L. M., Mohtar, W. H. M. W., Khan, T., Jusoh, H., Sarwono, A., Ali, M. M., Muda, Z. C., Nazri, F. M., Isa, M. H., Ghanim, A. A. J., Ahmad, A., Rasdi, N. W., & Basri, N. A. N. (2021). Physicochemical and leaching properties of coal ashes from Malaysian coal power plant. *Chemical Physics Letters*, *769*(2), 420–431.

Majaliwa, N., Kibazohi, O., & Alminger, M. (2019). Optimization of process parameters for mechanical extraction of banana juice using response surface methodology. *Journal of Food Science and Technology, 56*(9), 4068–4075.

Maliki, A. I. F. A., Shahidan, S., Ali, N., Hannan, N. I. R. R., Zuki, S. S. Z., Ibrahim, M. H. W., Azmi, M. A. M., & Rahim, M. A. (2017). Compressive and tensile strength for concrete containing coal bottom ash. *IOP Conference Series: Materials Science and Engineering, 271*(1), 2055–2064.

Majhi, R. K., & Nayak, A. N. (2019). Properties of Concrete Incorporating Coal Fly Ash and Coal Bottom Ash. J*ournal of The Institution of Engineers (India): Series A*, *100*(3), 459–469.

Mangi, S. A., Ibrahim, M. H. W., Jamaluddin, N., Arshad, M. F., Memon, F. A., Jaya, R. P., & Shahidan, S. (2018). A review on potential use of coal bottom ash as a supplementary cementing material in sustainable concrete construction. *International Journal of Integrated Engineering*, *10*(9), 127–135.

Mangi, S. A., Ibrahim, M. H. W., Jamaluddin, N., Arshad, M. F., Memon, S. A., & Shahidan, S. (2019). Effects of grinding process on the properties of the coal bottom ash and cement paste. *Journal of Engineering and Technological Sciences*, *51*(1), 1–13.

Manojkumar, N., Muthukumaran, C., & Sharmila, G. (2022). A comprehensive review on the application of response surface methodology for optimization of biodiesel production using different oil sources. *Journal of King Saud University - Engineering Sciences*, *34*(3), 198–208.

Marto, A., & Tan, C. S. (2016). Properties of Coal Bottom Ash from Power Plants in Malaysia and its Suitability as Geotechnical Engineering Material. *Jurnal Teknologi*, *5*(11), 1–10.

Mhaya, A. M., Shahidan, S., Algaifi, H. A., Zuki, S. S. M., Benjeddou, O., Ibrahim, M. H. W., & Huseien, G. F. (2022). Thermal conductivity of coconut shell-incorporated concrete: A systematic assessment via theory and experiment. *Sustainability (Switzerland)*, *14*(23), 67–79.

Moodi, Y., Mousavi, S. R., Ghavidel, A., Sohrabi, M. R., & Rashki, M. (2018). Using Response Surface Methodology and providing a modified model using whale algorithm for estimating the compressive strength of columns confined with FRP sheets. *Construction and Building Materials*, *183*(9), 163–170.

Mosaberpanah, M. A., Eren, O., & Tarassoly, A. R. (2019). The effect of nano-silica and waste glass powder on mechanical, rheological, and shrinkage properties of UHPC using response surface methodology. *Journal of Materials Research and Technology*, *8*(1), 804–811.

Muthusamy, K., Jamaludin, N. F. A., Kamaruzzaman, M. N., Ahmad, M. Z., Zamri, N. A., & Budiea, A. M. A. (2021). Compressive strength of palm oil clinker lightweight aggregate concrete containing coal bottom ash as sand replacement. *Materials Today: Proceedings*, *46*(1), 1724–1728.

Muthusamy, K., Rasid, M. H., Jokhio, G. A., Budiea, A. M. A., Hussin, M. W., & Mirza, J. (2020). Coal bottom ash as sand replacement in concrete: A review. *Construction and Building Materials*, *236*(7), 507–518.

Nazerian, M., Kamyabb, M., Shamsianb, M., Dahmardehb, M., & Kooshaa, M. (2018). Comparison of response surface methodology (RSM) and artificial neural networks (ANN) towards efficient optimization of flexural properties of gypsum-bonded fiberboards. *Cerne*, *24*(1), 35–47.

Nematzadeh, M., Shahmansouri, A. A., & Fakoor, M. (2020). Post-fire compressive strength of recycled PET aggregate concrete reinforced with steel fibers: Optimization and prediction via RSM and GEP. *Construction and Building Materials, 252*(7), 57–64.

Ngo, S. H., & Huynh, T. P. (2020). Evaluation of the performance of concrete containing coal bottom ash through the nondestructive tests and microstructure analysis. *International Journal on Emerging Technologies, 11(*2), 308–313.

Nudri, N. A., Ghani, W. A., Bachmann, R. T., Baharudin, B. T. H. T., Ng, D. K. S., & Said, M. S. M. (2021). Co-combustion of oil palm trunk biocoal/sub-bituminous coal fuel blends. *Energy Conversion and Management: X, 10*(2), 72–81.

Nur, W., Wan, F., Ismail, M. A., Lee, H., Seddik, M., Kumar, J., Warid, M., & Ismail, M. (2020). Mixture optimization of high-strength blended concrete using central composite design. *Construction and Building Materials, 243(6),* 8251.

Pal, S., Shariq, M., Abbas, H., Pandit, A. K., & Masood, A. (2020). Strength characteristics and microstructure of hooked-end steel fiber reinforced concrete containing fly ash, bottom ash and their combination. *Construction and Building Materials*, *247*(7), 8530–8542.

Prabhu, M. V., & Karthikeyan, R. (2018). Comparative studies on modelling and optimization of hydrodynamic parameters on inverse fluidized bed reactor using ANN-GA and RSM. *Alexandria Engineering Journal*, *57*(4), 3019–3032.

Pashaei, H., Ghaemi, A., Nasiri, M., & Karami, B. (2020). Experimental modeling and optimization of CO 2 absorption into piperazine solutions using RSM-CCD methodology. *ACS Omega*, *5*(15), 8432–8448.

Poorarbabi, A., Ghasemi, M., & Moghaddam, M. A. (2020). Concrete compressive strength prediction using non-destructive tests through response surface methodology. *Ain Shams Engineering Journal, 11*(4), 939–949.

Rafieizonooz, M., Mirza, J., Salim, M. R., Hussin, M. W., & Khankhaje, E. (2016). Investigation of coal bottom ash and fly ash in concrete as replacement for sand and cement. *Construction and Building Materials*, *116*(7), 15–24.

Ramzi, N. I. R., Shahidan, S., Maarof, M. Z., & Ali, N. (2016). Physical and chemical properties of coal bottom ash (CBA) from Tanjung Bin power plant. *IOP Conference Series: Materials Science and Engineering*, *160*(1), 56–67.

Rastegar, Z., & Ghaemi, A. (2022). CO^2 absorption into potassium hydroxide aqueous solution: experimental and modeling. *Heat and Mass Transfer*, *58*(3), 365–381.

Rodriguez-alvaro, R., Seara-paz, S., Gonzalez-fonteboa, B., & Martinez-abella, F. (2021). Use of granular coal combustion products as aggregates in structural concrete: Effects on properties and recommendations regarding mix design. *Construction and Building Materials, 273*(1), 1690–1701.

Sourav, R., Haque, M., Ahmed, T., & Nahin, T. T. (2021). Comparison of artificial neural network (ANN) and response surface methodology (RSM) in predicting the compressive and splitting tensile strength of concrete prepared with glass waste and tin (Sn) can fiber. *Journal of King Saud University - Engineering Sciences, 35*(3), 185–199.

Said, K. A. M., & Amin, M. A. M. (2016). Overview on the response surface methodology (RSM) in extraction processes. *Journal of Applied Science & Process Engineering, 2*(1), 8–17.

Sachin, B., Rao, C. M., Naik, G. M., & Puneet, N. P. (2021). Influence of slide burnishing process on the surface characteristics of precipitation hardenable steel. *SN Applied Sciences, 3*(2), 223–231.

Salleh, S. Z., Awang Kechik, A., Yusoff, A. H., Taib, M. A. A., Nor, M. M., Mohamad, M., Tan, T. G., Ali, A., Masri, M. N., Mohamed, J. J., Zakaria, S. K., Boon, J. G., Budiman, F., & Teo, P. Ter. (2021). Recycling food, agricultural, and industrial wastes as pore-forming agents for sustainable porous ceramic production: A review. *Journal of Cleaner Production, 306*(9), 264–275.

Samson, N., Aondowase, A., & Shiwua, J. (2013). Effect of water-cement ratio on the compressive strength of gravel - crushed over burnt bricks concrete. *The International Institute for Science, Technology and Education, 3*(4), 74–82.

Shahbaz, M., Yusup, S., Inayat, A., Onoja, D., & Pratama, A. (2020). Application of response surface methodology to investigate the effect of different variables on conversion of palm kernel shell in steam gasification using coal bottom ash. *Applied Energy, 184*(12), 1306–1315.

Siddique, R. (2013). Compressive strength, water absorption, sorptivity, abrasion resistance and permeability of self-compacting concrete containing coal bottom ash. *Construction and Building Materials, 47*(5), 1444–1450.

Singh, M., & Siddique, R. (2013). Effect of coal bottom ash as partial replacement of sand on properties of concrete. *Resources, Conservation and Recycling, 72*(1), 20–32.

Singh, M., & Siddique, R. (2014). Compressive strength, drying shrinkage and chemical resistance of concrete incorporating coal bottom ash as partial or total replacement of sand. *Construction and Building Materials, 68*(8), 39–48.

Singh, M., & Siddique, R. (2015). Properties of concrete containing high volumes of coal bottom ash as fine aggregate. *Journal of Cleaner Production, 91*(3), 269–278.

Singh, M., & Siddique, R. (2016). Effect of coal bottom ash as partial replacement of sand on workability and strength properties of concrete. *Journal of Cleaner Production, 112*(11), 620–630.

Singh, N., Mithulraj, M., & Arya, S. (2018). Influence of coal bottom ash as fine aggregates replacement on various properties of concretes: A review. *Resources, Conservation and Recycling, 138*(3), 257–271.

Singh, N., Mithulraj, M., & Arya, S. (2019). Utilization of coal bottom ash in recycled concrete aggregates based self-compacting concrete blended with metakaolin. *Resources, Conservation and Recycling, 144*(2), 240–251.

Singh, N., Shehnazdeep, & Bhardwaj, A. (2020). Reviewing the role of coal bottom ash as an alternative of cement. *Construction and Building Materials, 233*(7), 276–283.

Sinkhonde, D., Onchiri, R. O., Oyawa, W. O., & Mwero, J. N. (2021). Response surface methodology-based optimisation of cost and compressive strength of rubberised concrete incorporating burnt clay brick powder. *Heliyon, 7*(12), 8565–8573.

Sultana, N., Hossain, S. M. Z., Alam, M. S., Hashish, M. M. A., & Islam, M. S. (2020). An experimental investigation and modeling approach of response surface methodology coupled with crow search algorithm for optimizing the properties of jute fiber reinforced concrete. *Construction and Building Materials, 243(9),* 8216–8223.

Sun, Q., Zhu, H., Li, H., Zhu, H., & Gao, M. (2018). Application of response surface methodology in the optimization of fly ash geopolymer concrete. *ISA Transactions, 48*(4), 45–52.

Waliyo, R. A., & Noor, N. M. (2022). Investigation on material physical properties for application in seawater-RHA concrete added with coal bottom ash. IOP Conference Series: *Earth and Environmental Science, 1022*(1), 2051–2064.

Zhang, Q., Feng, X., Chen, X., & Lu, K. (2020). Mix design for recycled aggregate pervious concrete based on response surface methodology. *Construction and Building Materials, 259*(10), 9776–9783.

APPENDIX E

E1: Published Paper

Ku Meh, K. M. F., Shahidan, S., Shamsuddin, S.-M., Mohd Zuki, S. S., & Senin, M. S. (2022). An Experimental Investigation of Coal Bottom Ash as Sand Replacement. International Journal of GEOMATE, Vol. 23, Issue 99, pp. 17–24. https://doi.org/10.21660/2022.99.3515.